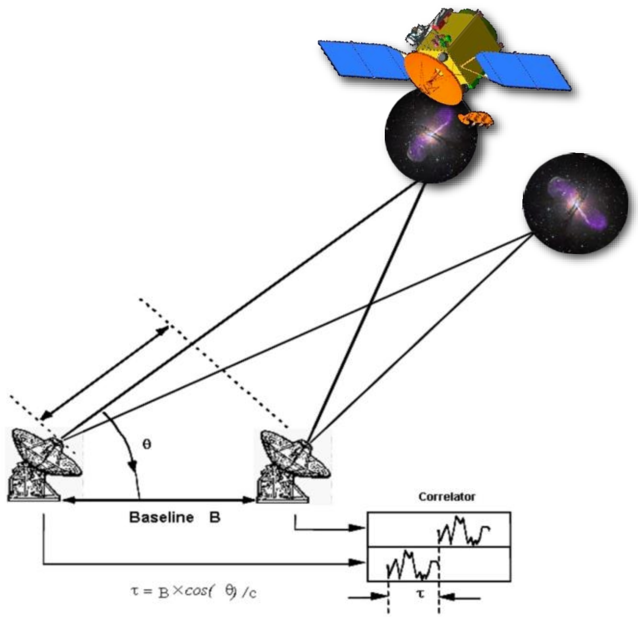
VLBI Futures, 12 March 2018

A vision for the 2020s for Reference Frames and Global Astrometry



Christopher S. Jacobs, *Jet Propulsion Laboratory, California Institute of Technology*

D. Gordon, A. De Witt, A. Bertarini, C. Garcia-Miro,, S. Horiuchi,

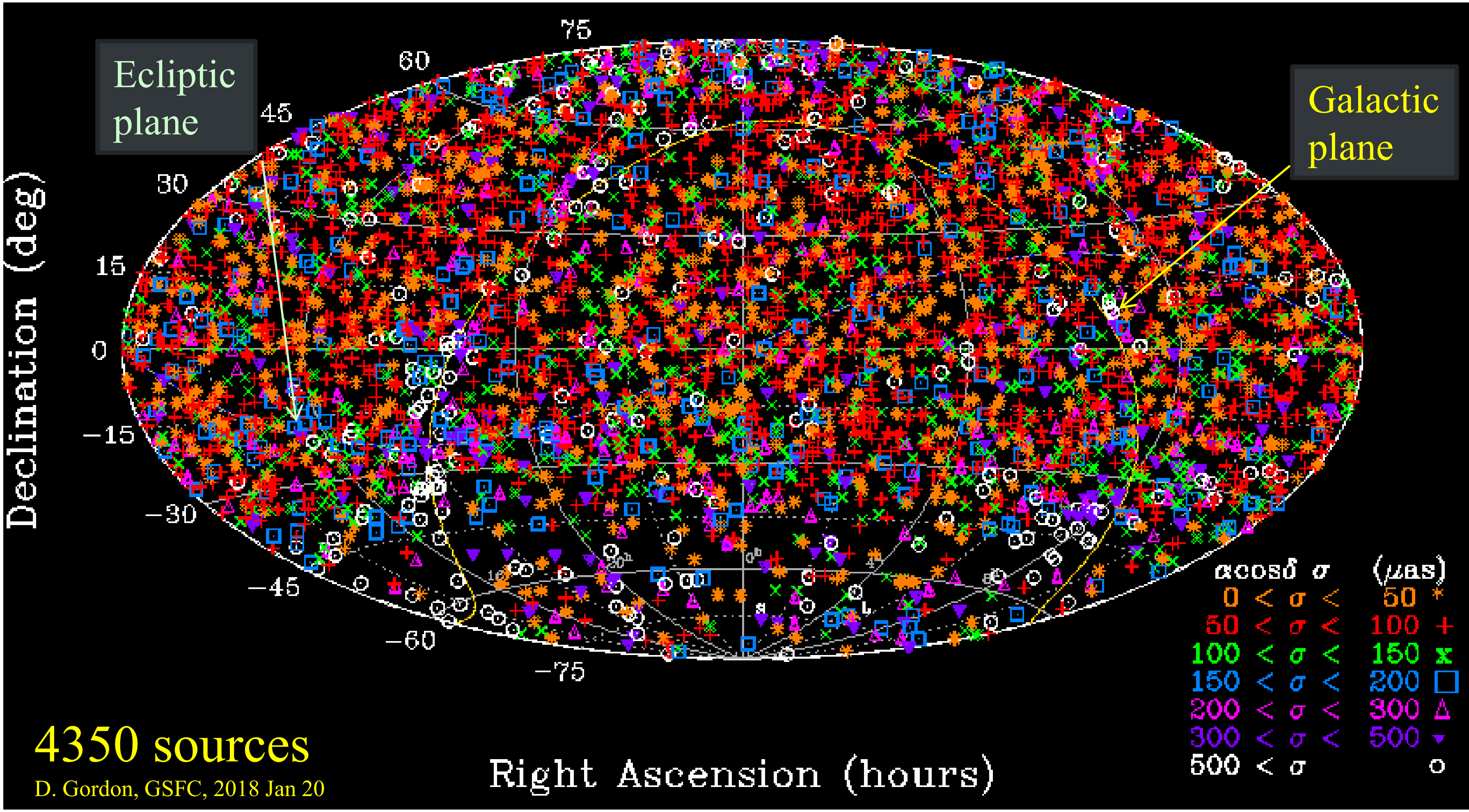
J. McCallum, M. Mercolino, J. Quick, L. Snedeker

Overview: Current Status of Global Celestial Frames

VLBI at cm wavelengths:

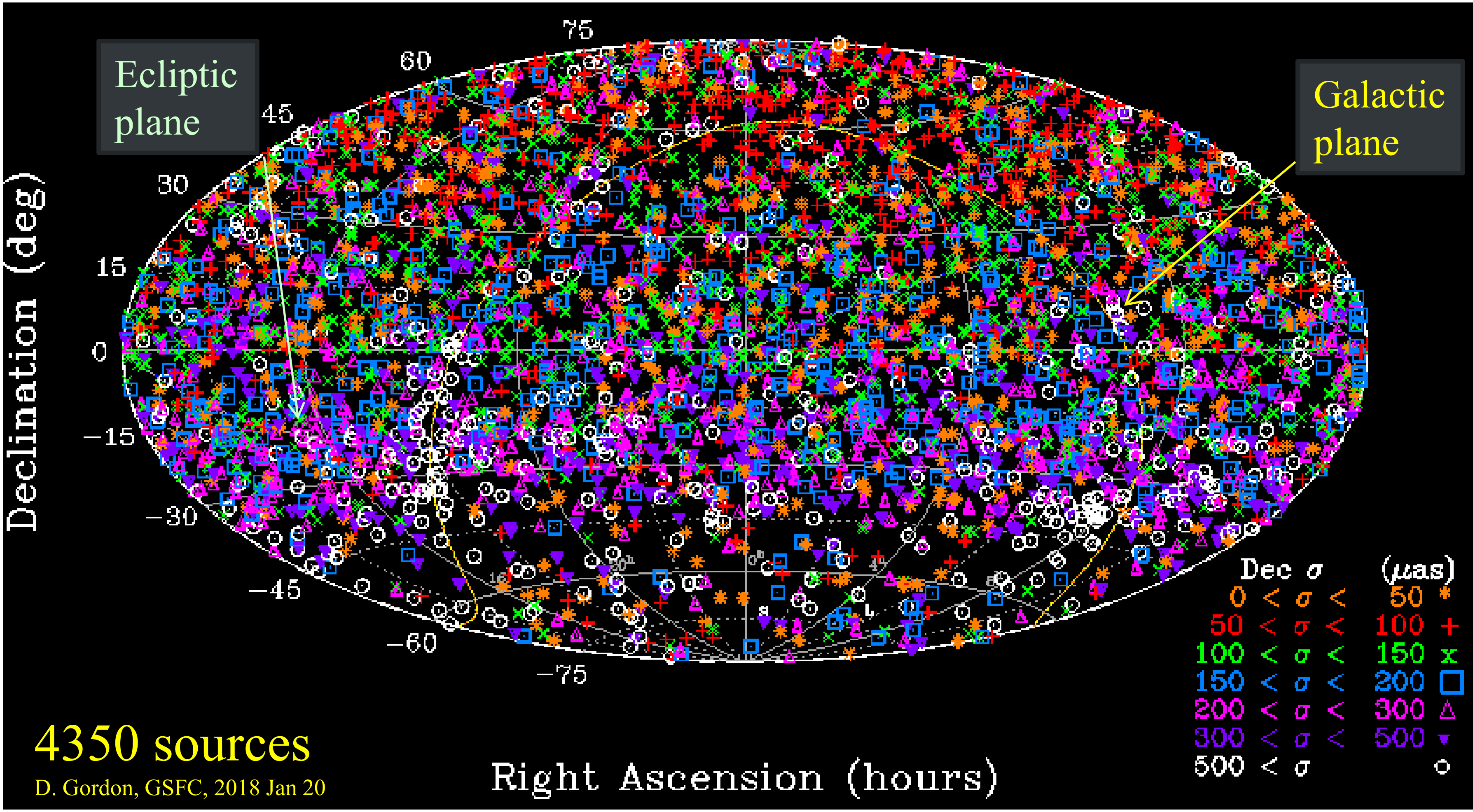
- SX (8 GHz, 3.6cm) has been only sub-mas frame until last 10 years
  (e.g. *Ma+, ICRF1, 1998, Ma+, ICRF2, 2009*)
- K-band (24 GHz, 1.2cm) now sub-mas (*Lanyi+, 2010; de Witt+, 2016, 2017*)
- X/Ka (32 GHz, 9mm) also sub-mas (*Jacobs+, 2016, 2017*)
- Accuracy limited by VLBI systematics due to
  weak southern geometry: More southern stations?
  troposphere: WVRs?
  clocks: distributed clocks?
  source structure: move to higher frequencies
- Gaia optical: data release #1 is sub-mas for auxiliary quasar solution (*Prusti+, 2017*)
  Final catalog should be sub 100 μas for brighter quasars

SX (8.4 GHz, 3.6cm) *VLBA+~ 100 other IVS*



- Strengths:
  - 4350 sources
  - Excellent coverage North of δ -30 deg
  - median precision < 50 μas
  - SX's 12 million observations, 40 years
  - over 100 stations contributed
- Weaknesses:
  - Poor coverage south of δ -40 deg
  - only 20% of sources in > 10 sessions
  - source structure worse than K or XKa.

SX (8.4 GHz, 3.6cm): Dec precision weaker than RA



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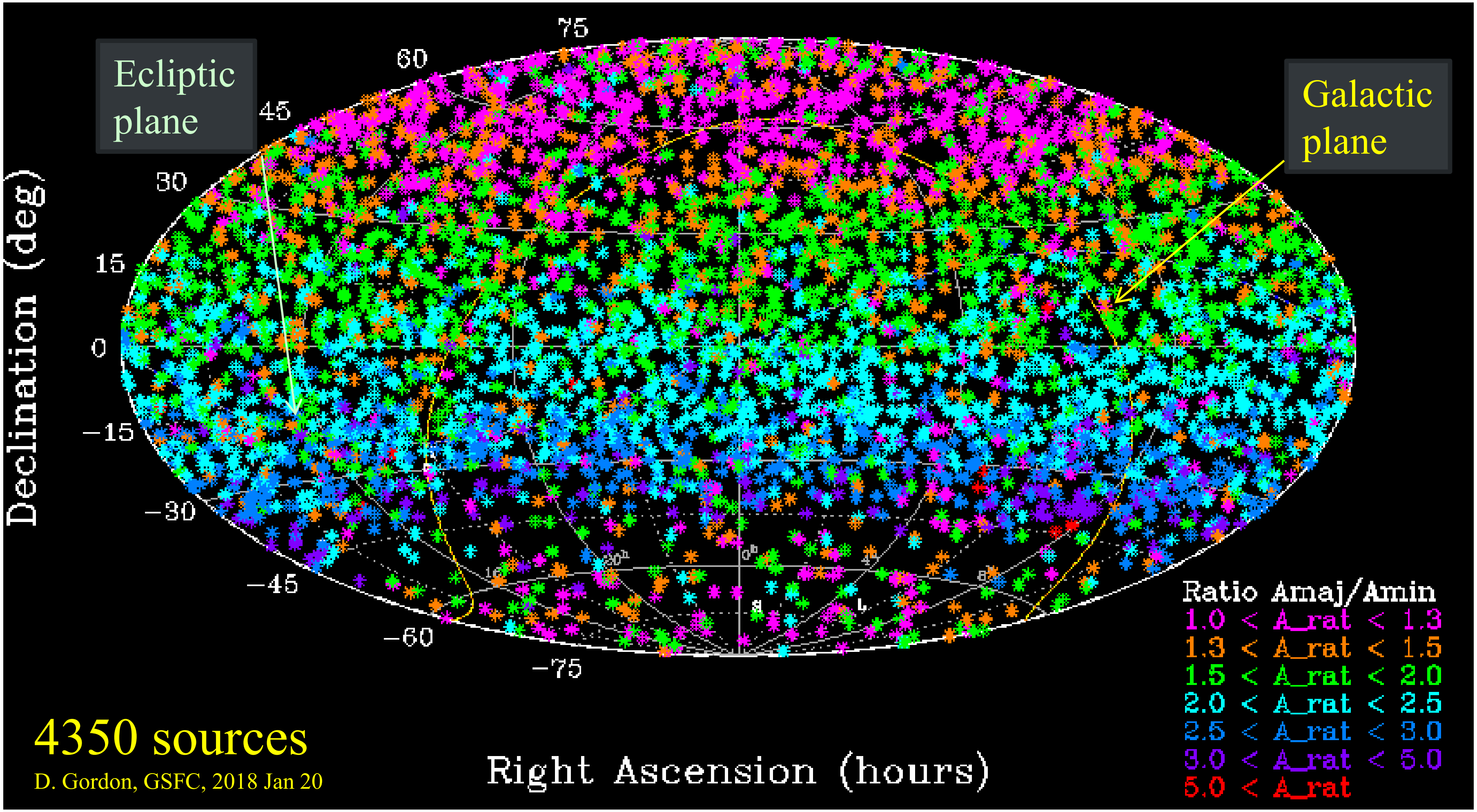
SX (8.4 GHz, 3.6cm): Dec precision 3X worse RA in south



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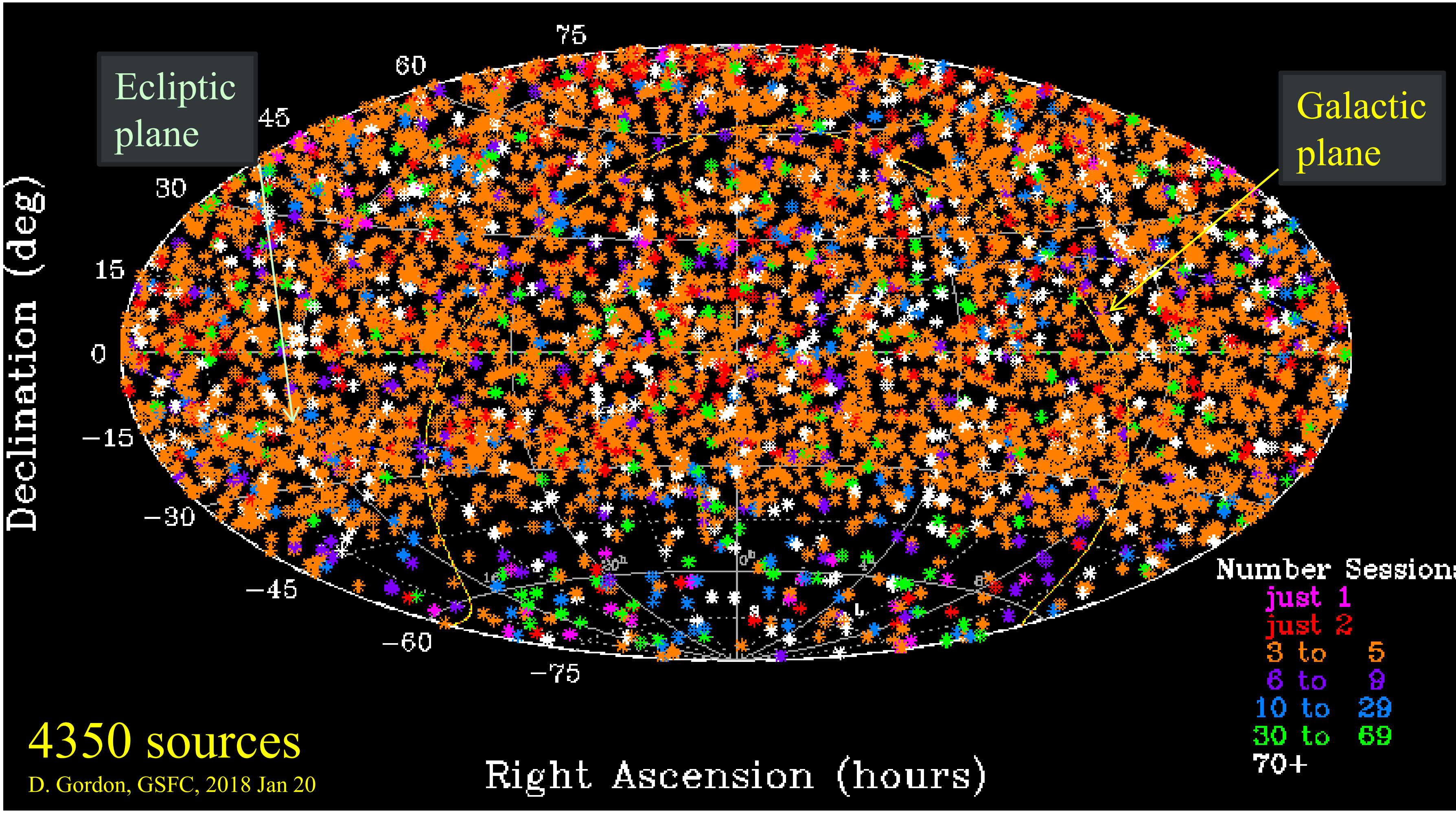
SX: Number Sessions, ~800 > 10 sessions, rest 3-5 survey sessions



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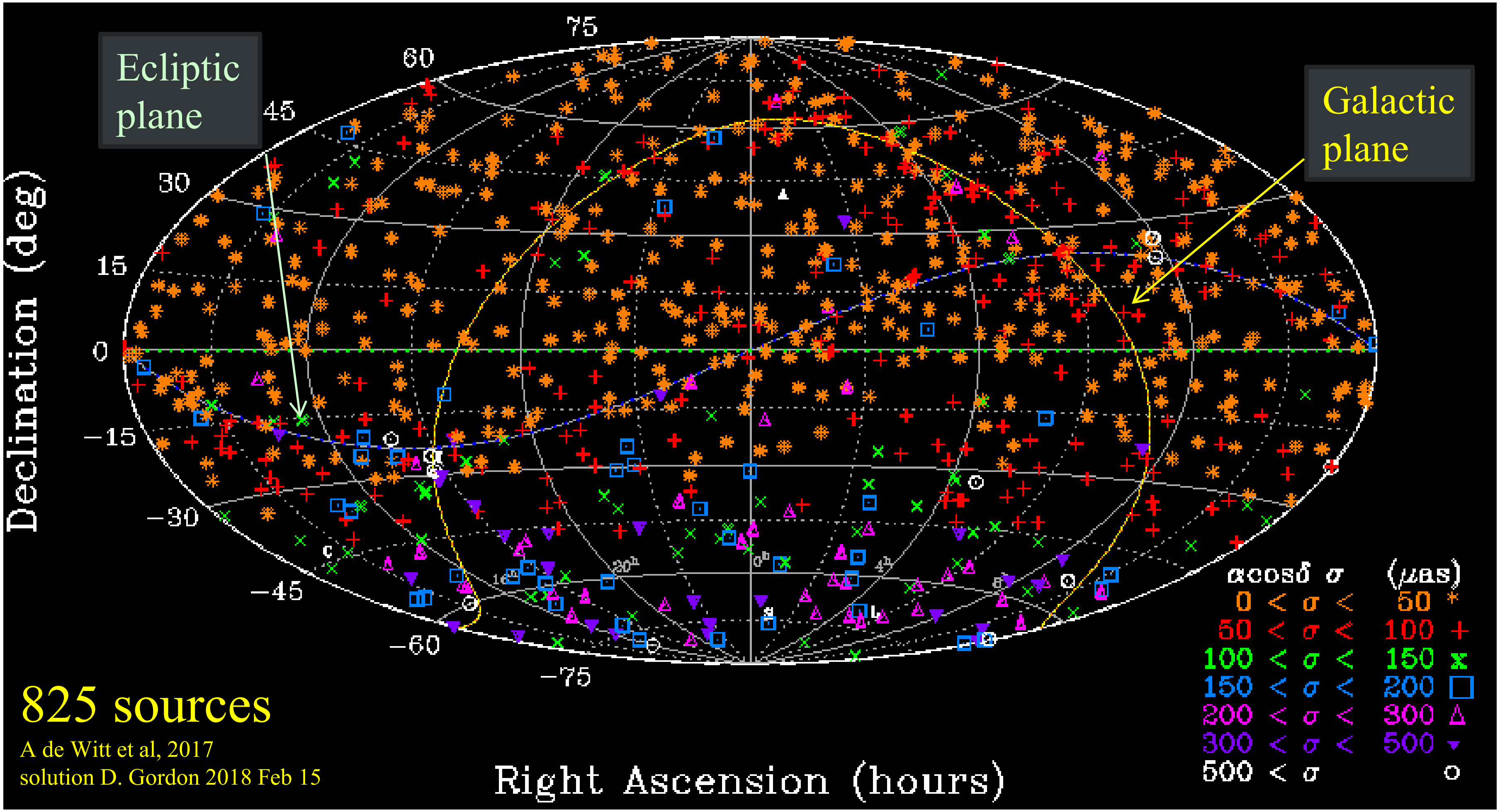
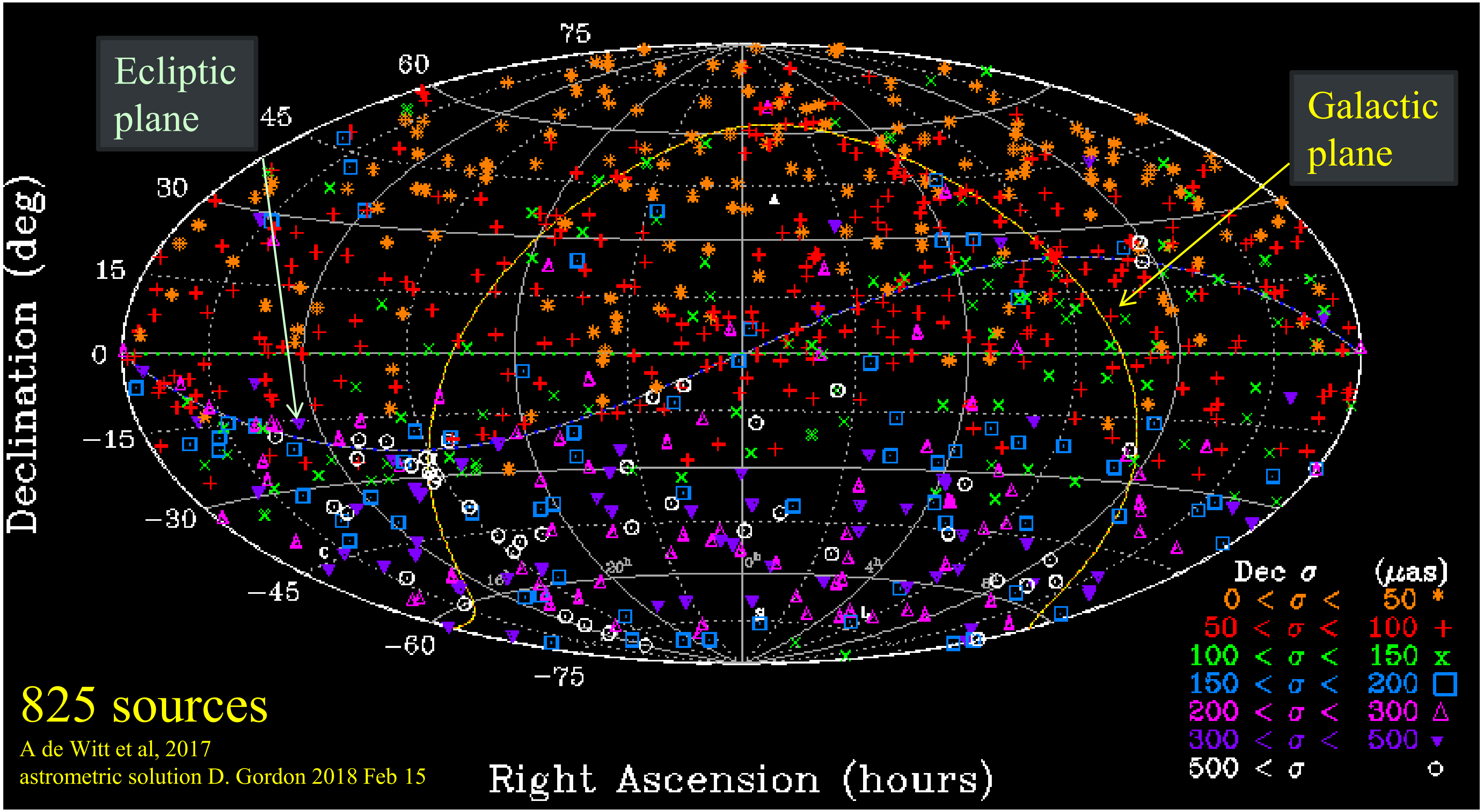
K (24 GHz, 1.2cm) *VLBA+ (S. Africa-Tasmania)*



- Strengths:
  - Uniform spatial density
  - Galactic plane sources (Petrov+ 2006)
  - less structure than S/X (3.6cm)
  - precision < 100 µas
  - needed ~ 0.4 million observations vs. SX's 12 million!

- Weaknesses:
  - Ionosphere only partially calibrated by GPS.
  - No solar plasma calibrations
  - South ($\delta < -30$ deg) weak due to limited HartRAO, South Africa to Hobart, Tasmania data

K (24 GHz, 1.2cm): Dec precision weaker than RA



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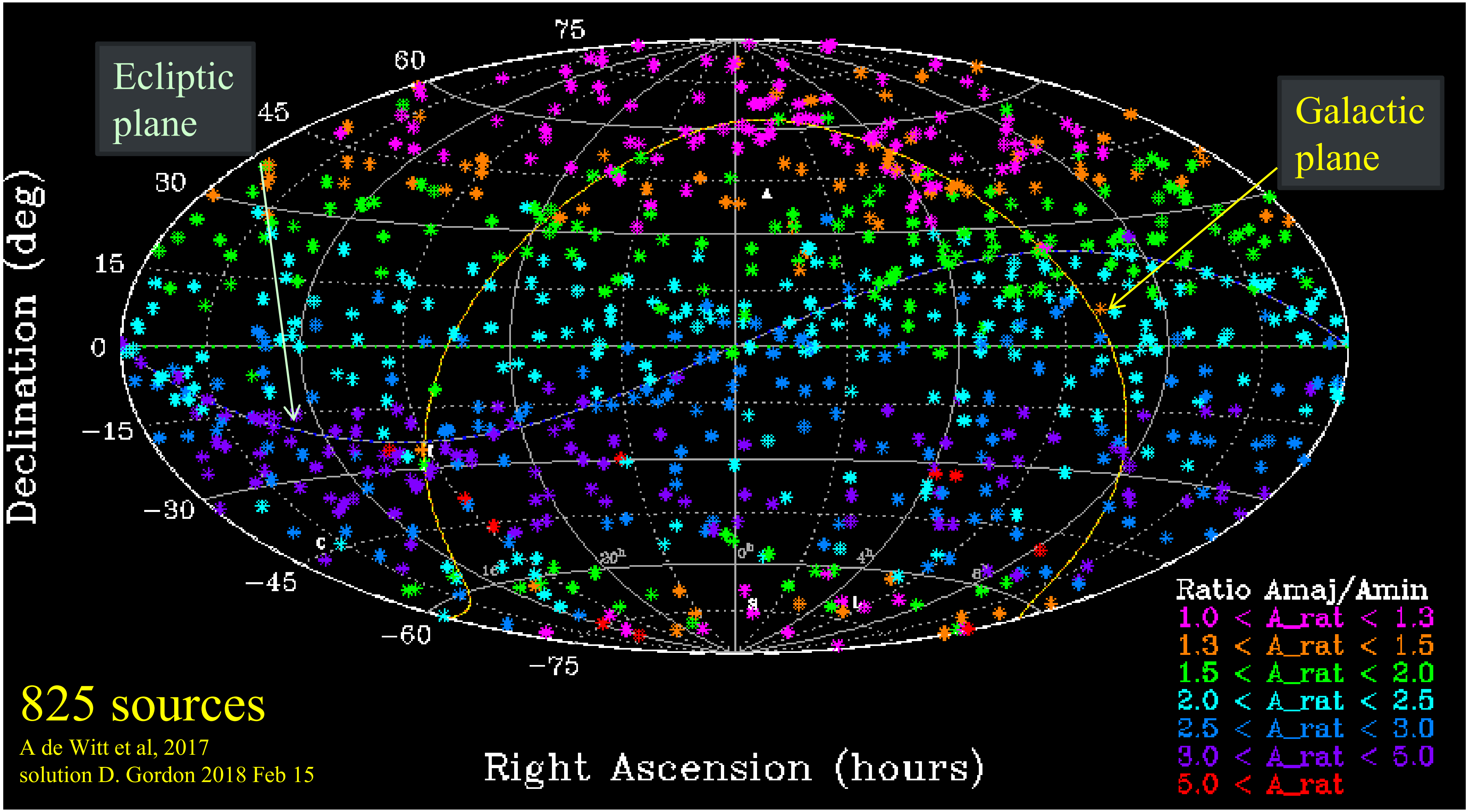

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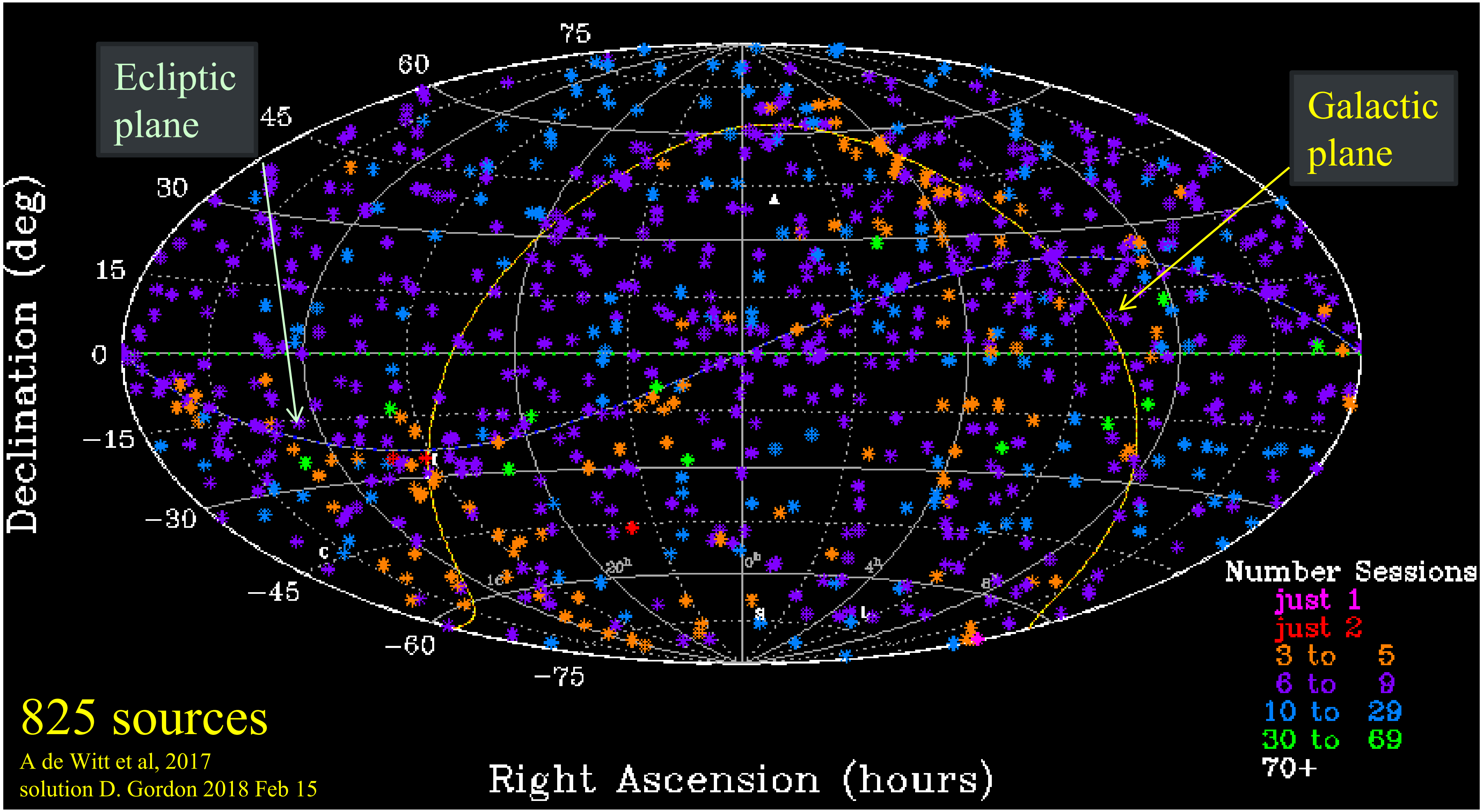
K (24 GHz, 1.2cm): Number sessions 6-9



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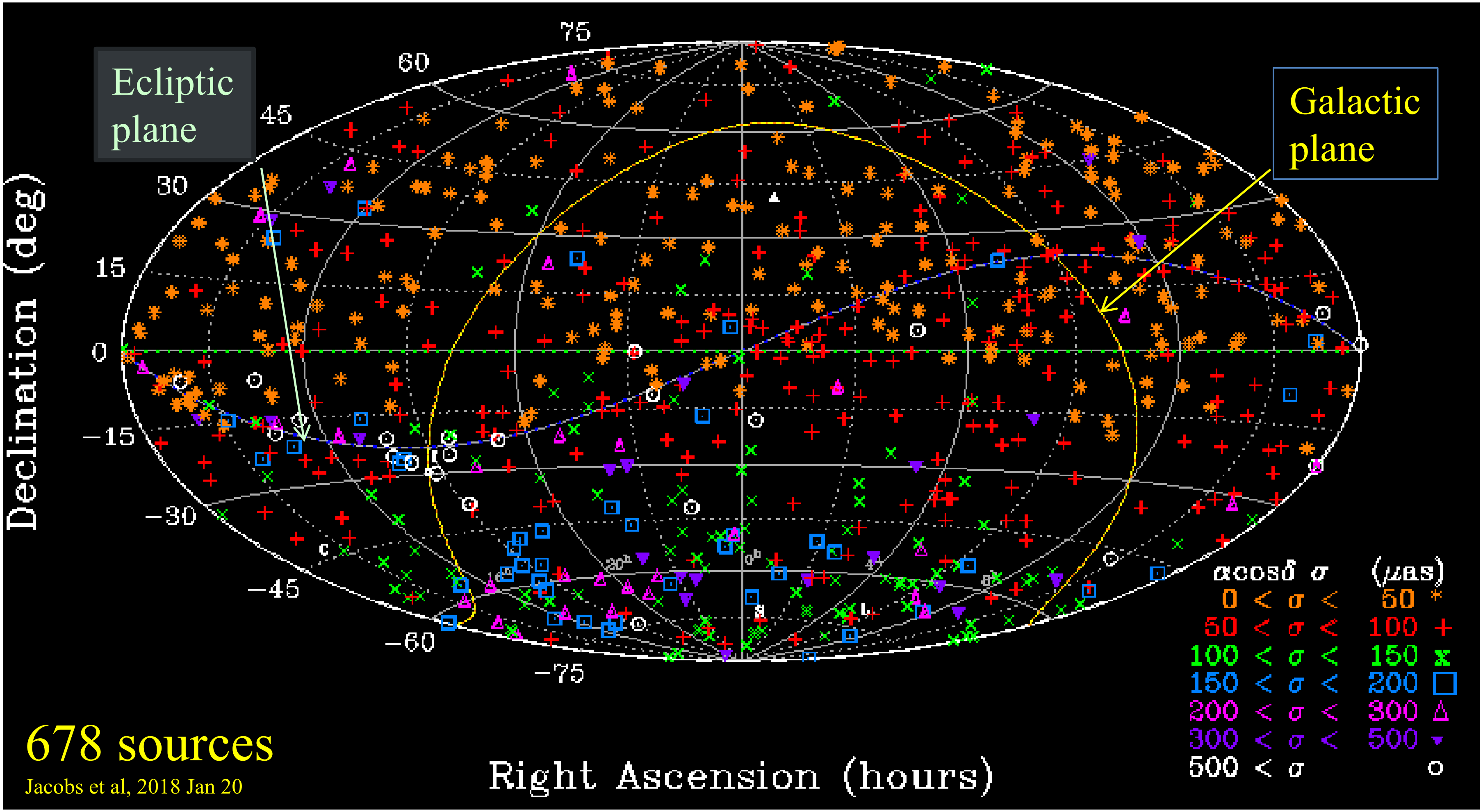
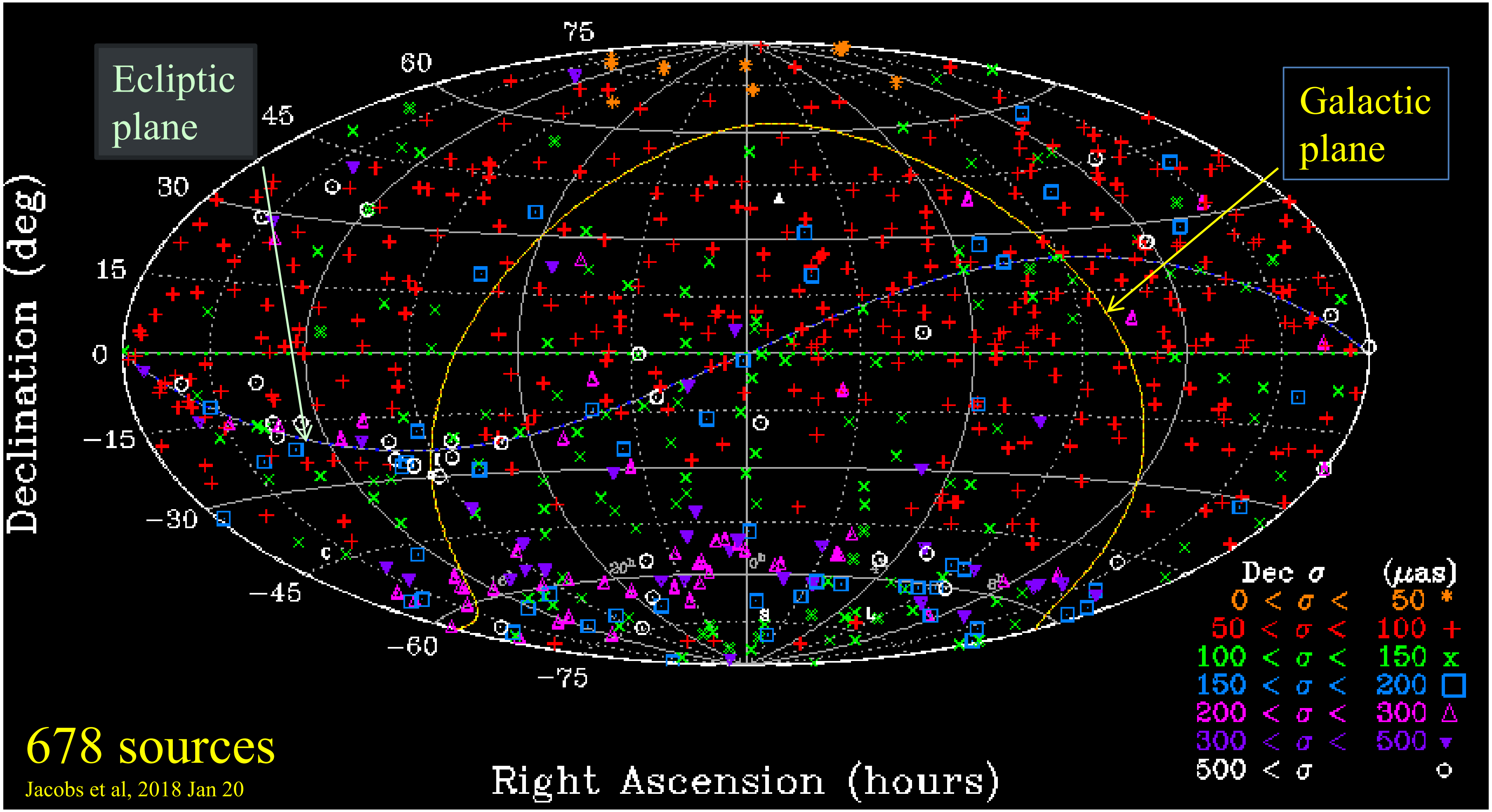
Ka (32 GHz, 9mm) Combined NASA/ESA Network



- Strengths:
  - Uniform spatial density
  - less structure than S/X (3.6cm)
  - precision < 100 μas
  - needed only 70K observations vs. SX's 12 million!

- Weaknesses:
  - Poor near Galactic center due to inter-stellar media scattering
  - South weak due to limited time on ESA's Argentina station
  - Limited Argentina-California data makes vulnerable to δ zonals
  - Limited Argentina-Australia weakens δ from -45 to -60 deg

X/Ka (32 GHz): Dec precision weaker, esp. δ -45 to -60



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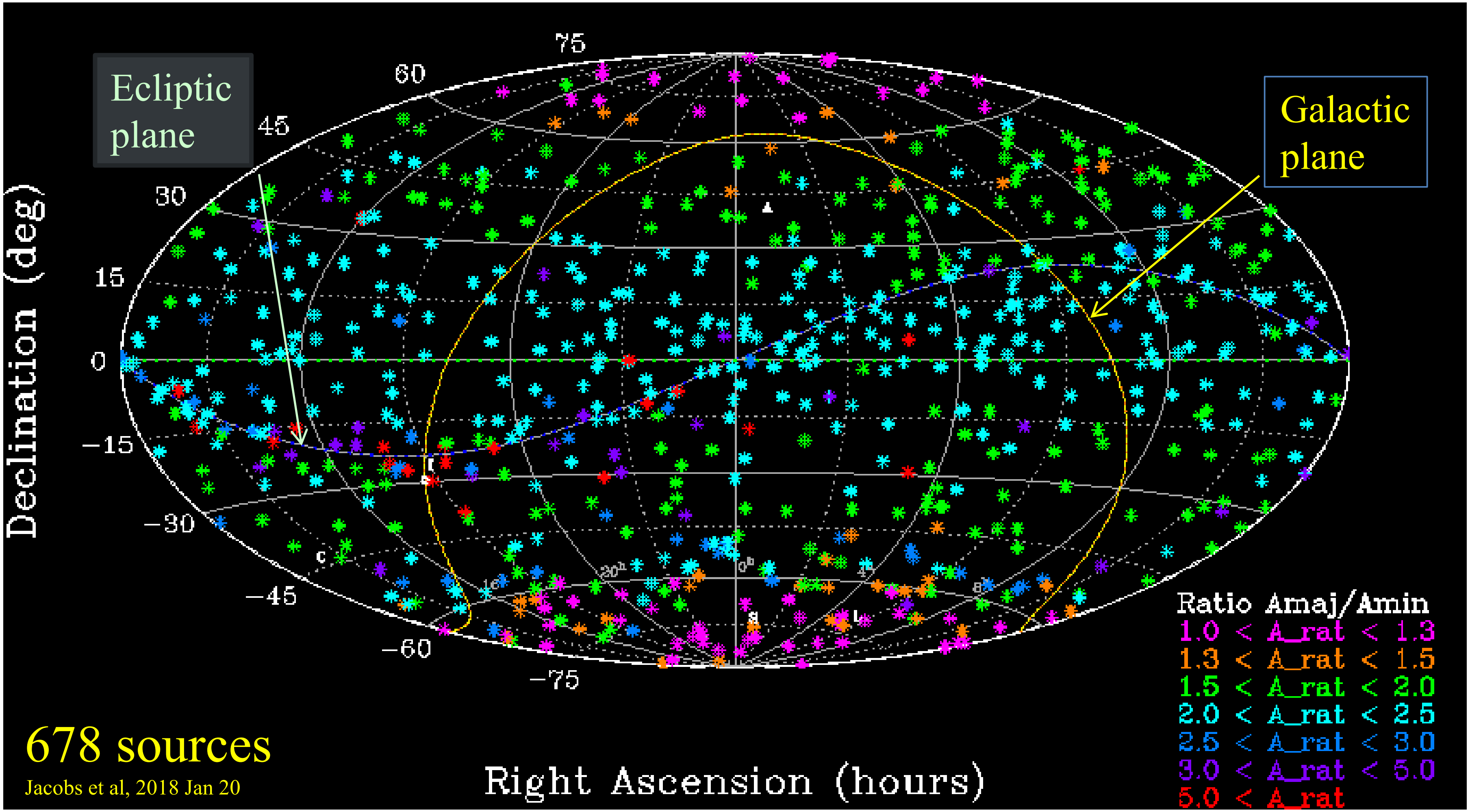

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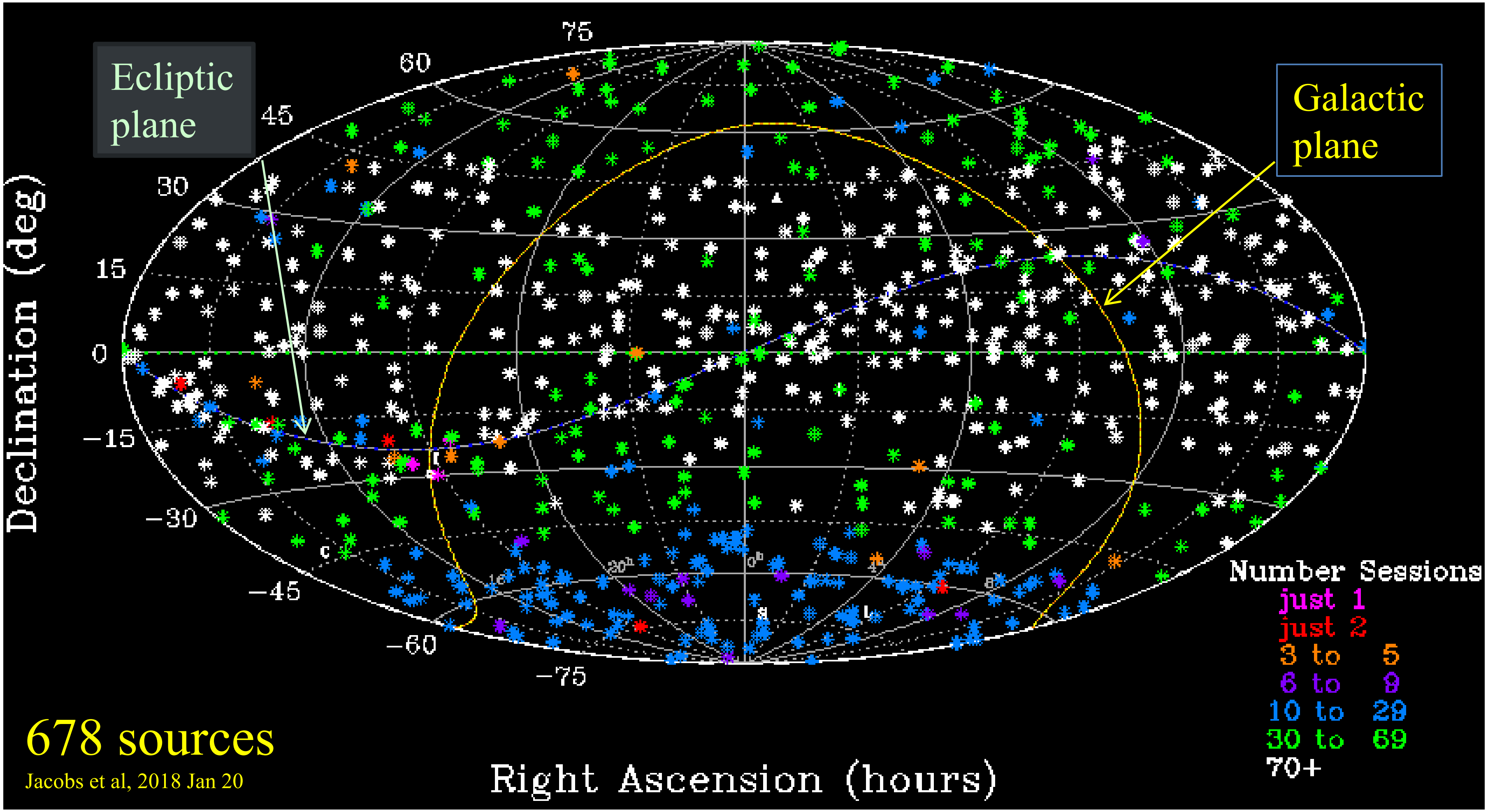
X/Ka (32 GHz): Number sessions better than SX or K



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Global Astrometry: path to progress

- **Source structure:**
  Source more compact at higher frequency
  Move astrometry to K or XKa

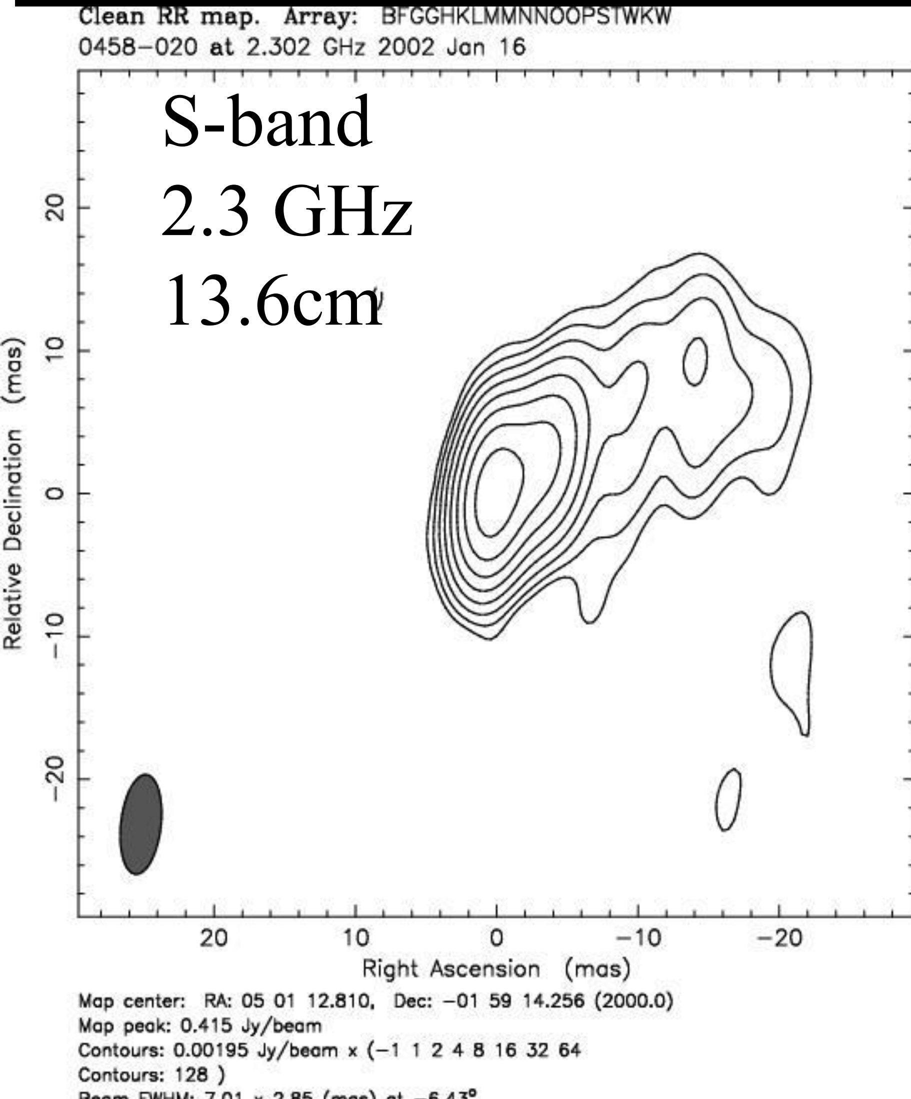
- **Troposphere:** Wet troposphere fluctuations are major error
  Build in WVRs

- **Clocks: Achieve common clocks**
  distribute clocks to southwestern stations
  then continental stations. Technical Feasability? Method: fiber? Cost?

- **Geometry/Resolution:**
  VLBA does very well in the northern hemisphere
  but at far end of reach $\delta \sim$ -30 deg, loses accuracy.
  Astrometry would benefit from longer N-S baselines:
  southern outriggers?
  VLBA antennas in Mexico?
  at ALMA site?

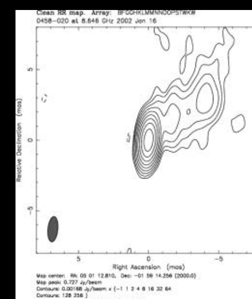
- **Sensitivity:**
  Current systems use 0.5 GHz analog @ 2bit = 2 Gbps
  Large antennas are expensive, so gain sensitivity via
  increased bandwidth: 8 to 32 Gbps?

Radio Source Structure vs. Frequency

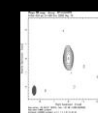


S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm



K-band
24 GHz
1.2cm



Q-band
43 GHz
0.7cm

The sources become better →
Less structure

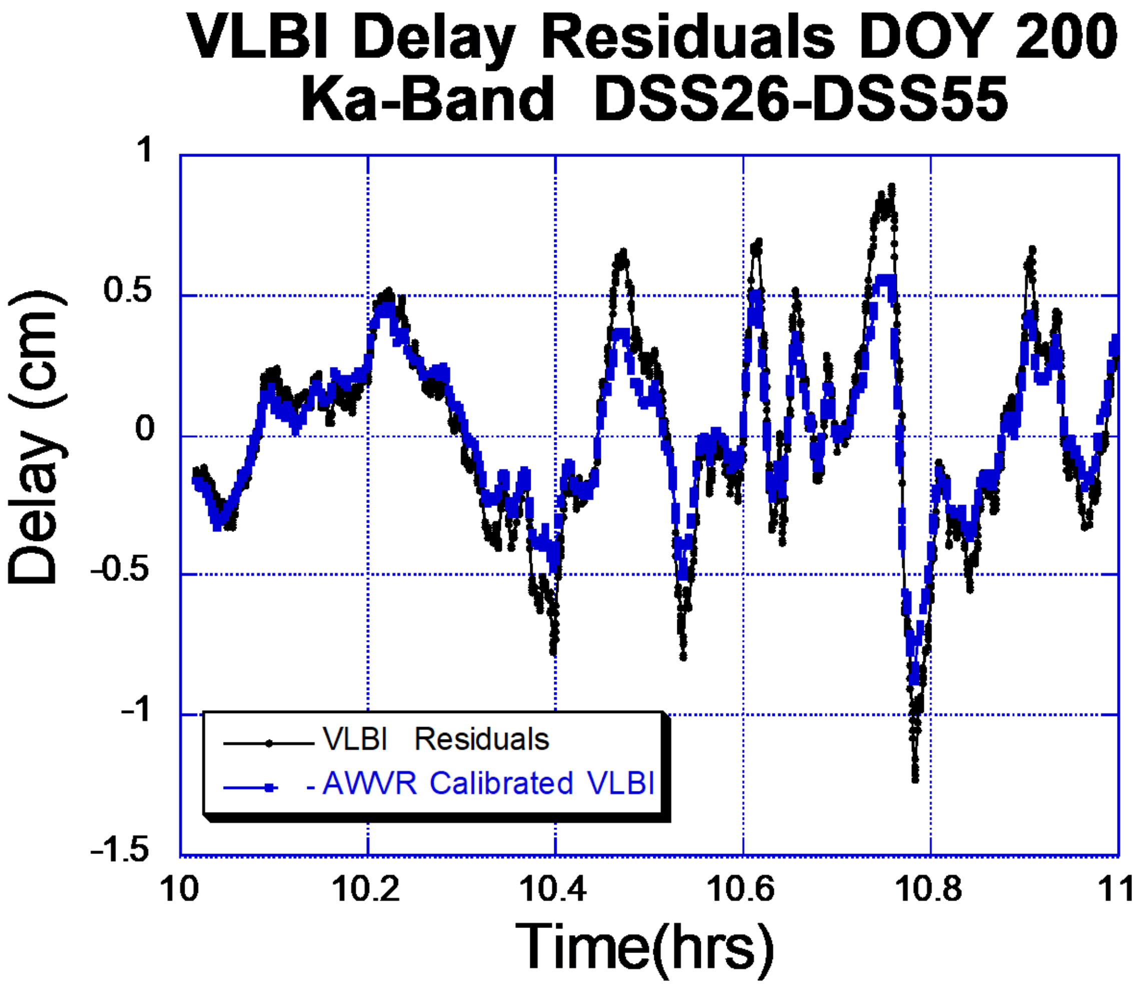
Ka-band
32 GHz
0.9cm

Images credit: Pushkarev & Kovalev A&A, 544, 2012 (SX); Charlot et al, AJ, 139, 2010 (KQ)

Calibrating Troposphere Turbulence

- JPL Advanced Water Vapor Radiometer
  - ~ 1 deg beam better matches VLBI
  - improved gain stability
  - improved conversion of brightness temperature to path delay

  Tanner & Riley, Radio Sci., 38, 2003
  http://adsabs.harvard.edu/abs/2003RaSc...38.8050T



- Initial demos show 1mm accuracy Goldstone-Madrid 8000 km baseline using X/Ka phase delays

  Jacobs et al, AAS Winter 2005.
  Bar Sever et al , IEEE, 2007.
  http://adsabs.harvard.edu/abs/2007IEEEP..95.2180B

- A-WVRs deployed at Goldstone/Madrid
  Seeking funding for Tidbinbilla, Aus

- A-WVR not used yet for Operations

NASA/ESA Deep Space Net Geometry

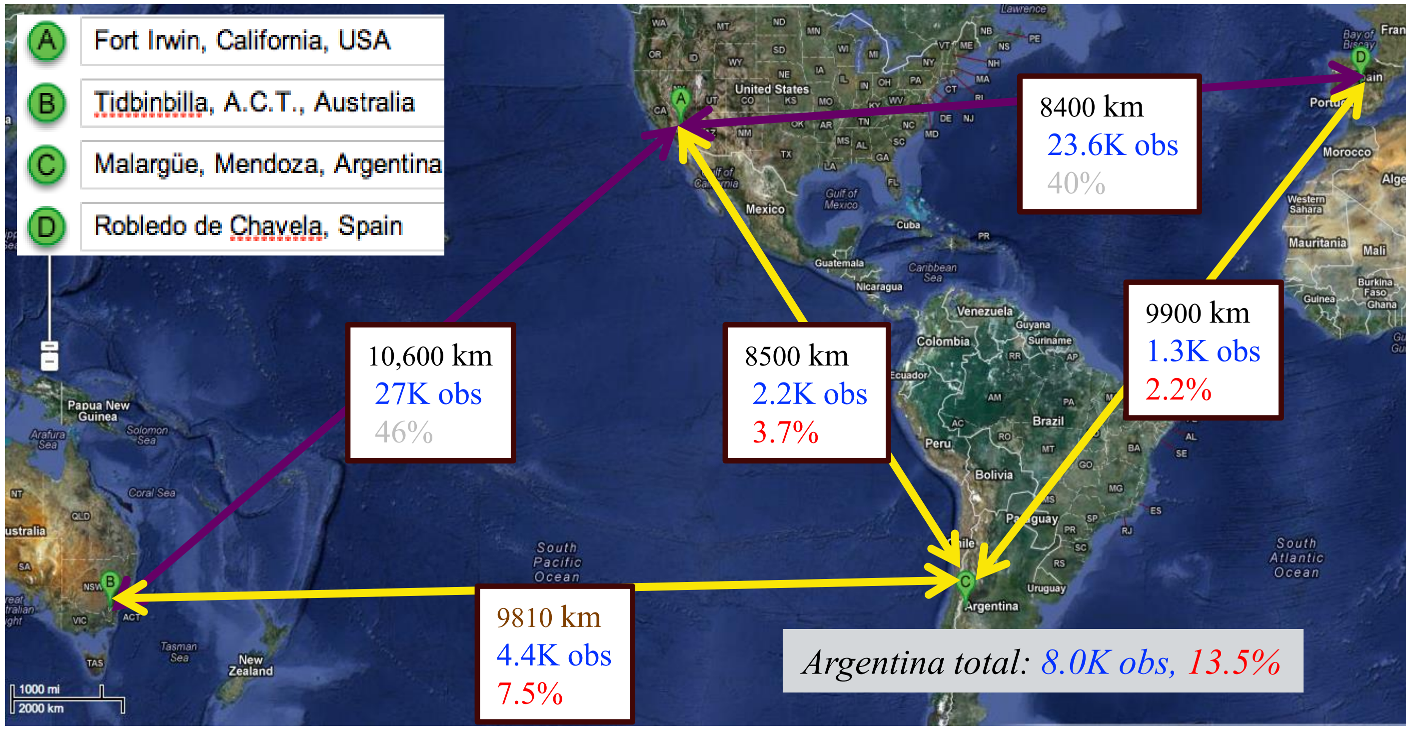
ESA Argentina to NASA-California under-observed by order of magnitude!

Baseline percentages

- Argentina is part of 3/5 baselines or 60% but only 13% of obs
- Aust- Argentina 7.5%
- Spain-Argentina 2.2%
- Calif- Argentina 3.7%

This baseline is under-observed by a factor of ~ 12.

More time on ESA's Argentina station would have a huge, immediate impact!!



Maps credit: Google maps

ESA's Argentina 35-meter antenna **adds 3 baselines** to DSN's 2 baselines

- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina

Three VLBI bands compare to better than 200 μas RMS
Gaia DR-1 precision ~ 500 μas. DR-2 vs. VLBI may reveal zonals

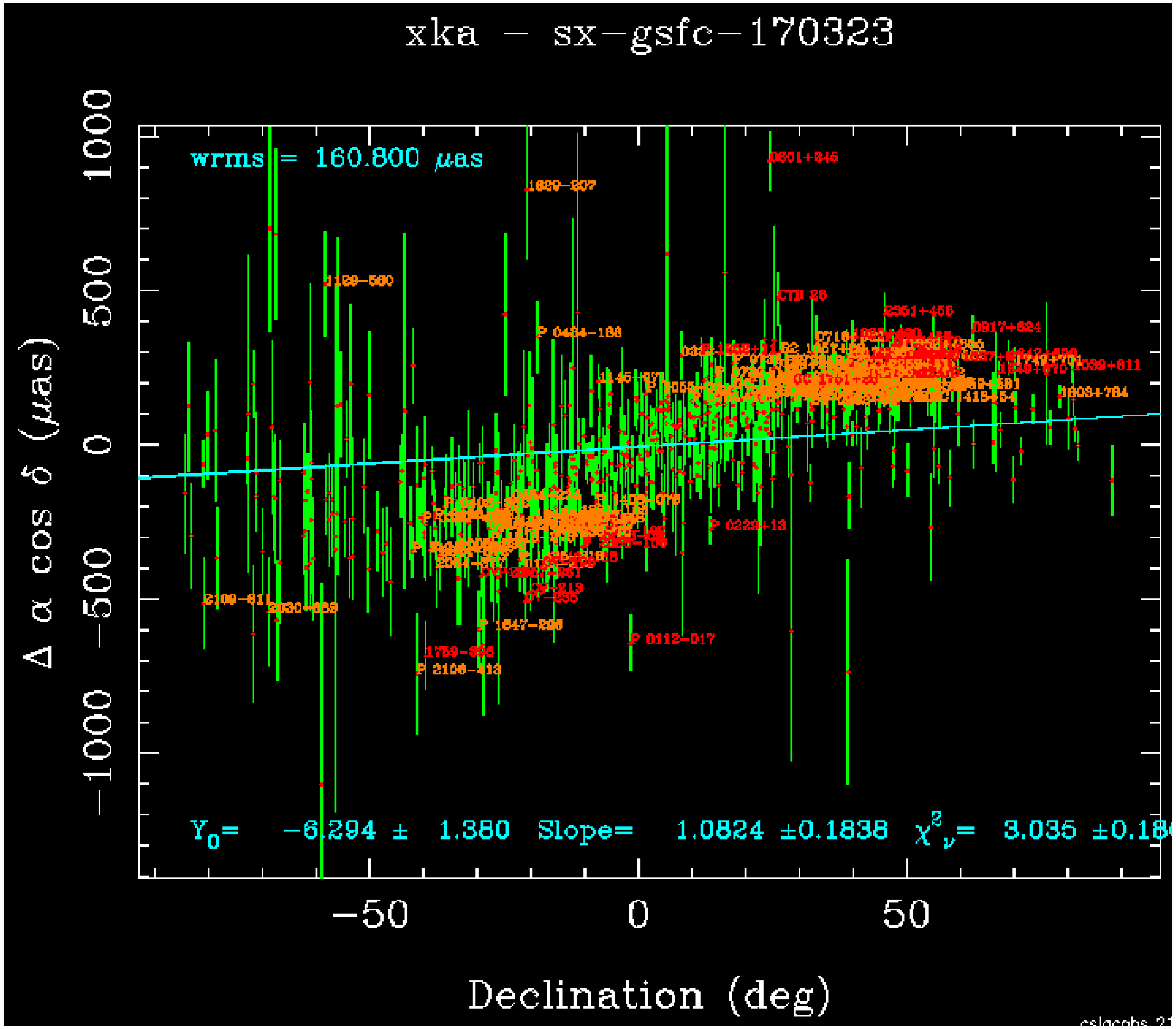
Zonal Errors

- ΔRA vs. Dec:
  ~300 μas in south, 200 μas in north
- Need 2 baselines to get 2 angles:
  California-Canberra: 24K obs
  California-Argentina: 2K obs

-> Need more California-Argentina data to overcome this 12 to 1 distortion in sampling geometry. ESA's Malargüe is key.

- Usuda, Japan 54-m XKa (2019) would improve North-South sampling geometry and thus control declination zonal differences.

XKa vs. SX: Zonal errors



Credit: SX astrometry, D. Gordon

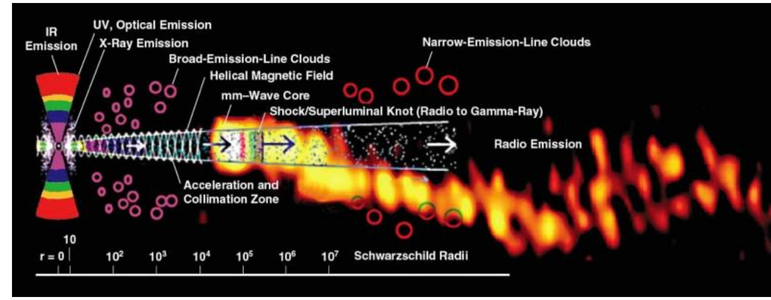
Sensitivity

- **Integrations are typically 1-2 minutes**
  Driven by
  Need to monitor large number of sources
  Coherence time is short at 24 and 32 GHz

- **Data rates**
  VLBA-only 2 Gbps SX and K
  DSN 2 Gbps (0.256 for Argentina)
  IVS 0.256 to 0.512 Gbps for large networks
  Limits much reference frame work to Fluxes > 100 mJy

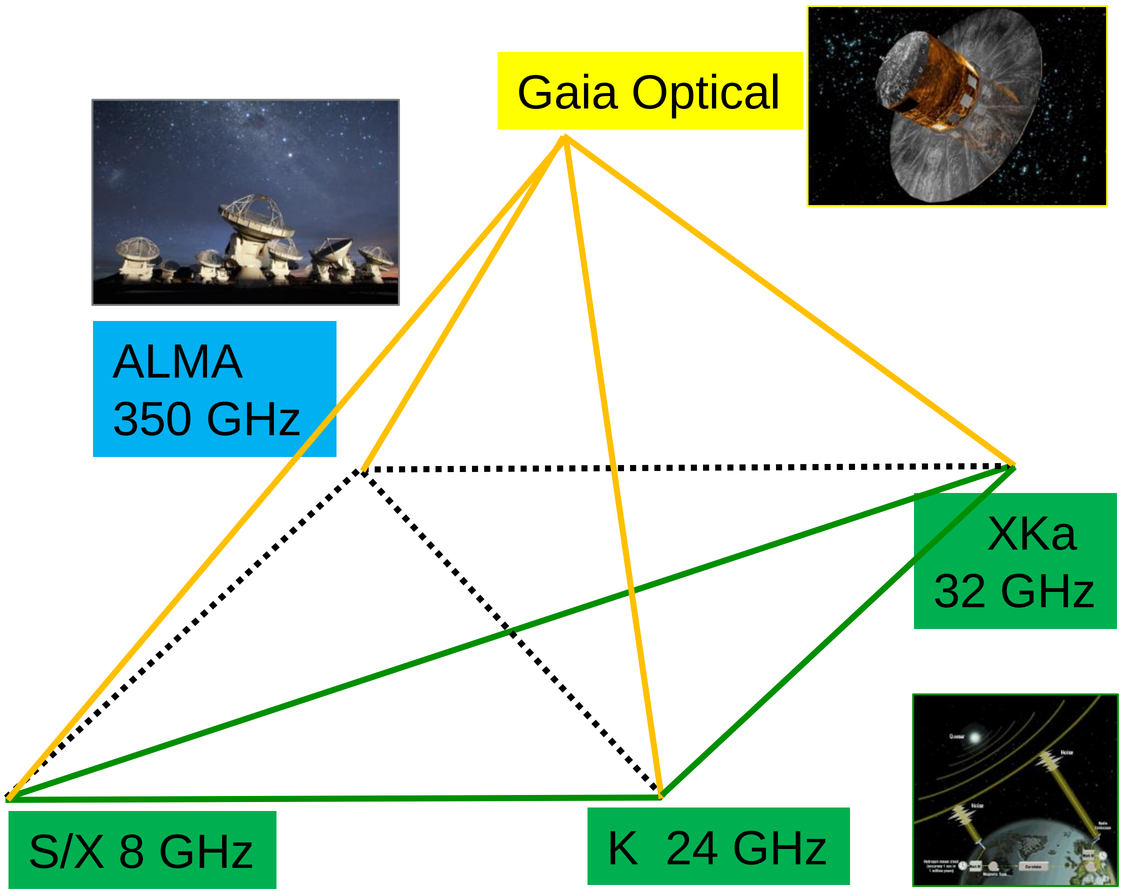
- **Future:**
  Increase data rates to 8 to 32 Gbps or more?
  Allows access to weaker sources and/or faster scans

Optical vs. Radio Frames



Credit: Marscher+, Krichbaum+

Systematics to be flushed out via Inter-comparison of multiple high precision frames.



Systematics:

Gaia: 60 mas beam sees
Host galaxy, foreground stars, etc.

ALMA: pilot obs bright end ~5^{mag}
Waiting on 10km+ configurations

VLBI: All bands need more
southern data

S/X: Source structure
K: Ionosphere
XKa: Argentina baselines
under-observed

Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. VLBI

	SX-band 8 GHz 3.6cm	K-band 24 GHz 1.2 cm	XKa-band 32 GHz 0.9 cm
# Observations	12 million	0.25 million	0.06 million
# sources	1926	473	405
# outliers > 5σ	100	13	6
% outliers	5.2 %	2.7 %	1.5 %
α wRMS	523 μas	431 μas	433 μas
δ wRMS	531 μas	453 μas	418 μas
R_x	-37 +- 13	-89 +- 24	57 +- 24
R_y	0 +- 11	14 +- 21	32 +- 21
R_z	-29 +- 13	-13 +- 23	21 +- 24
Δα vs. δ tilt (μas/deg)	-0.46 +- 0.25	-1.55 +- 0.53	-2.83 +- 0.58

Rx vulnerable
To trop errors

Hints that results improve by going to higher radio frequency
However, the above results do not use exact same objects (Jacobs+, IAU 330, 2017)

Summary: Global Astrometry

- **Current precisions ~ 100 μas or better at three bands:**
  SX 8 GHz 4200 objects, S-band RFI source structure
  K 24 GHz 825 objects, no dual band in cals (C/K?)
  XKa 32 GHz 680 objects, not supported by VLBA

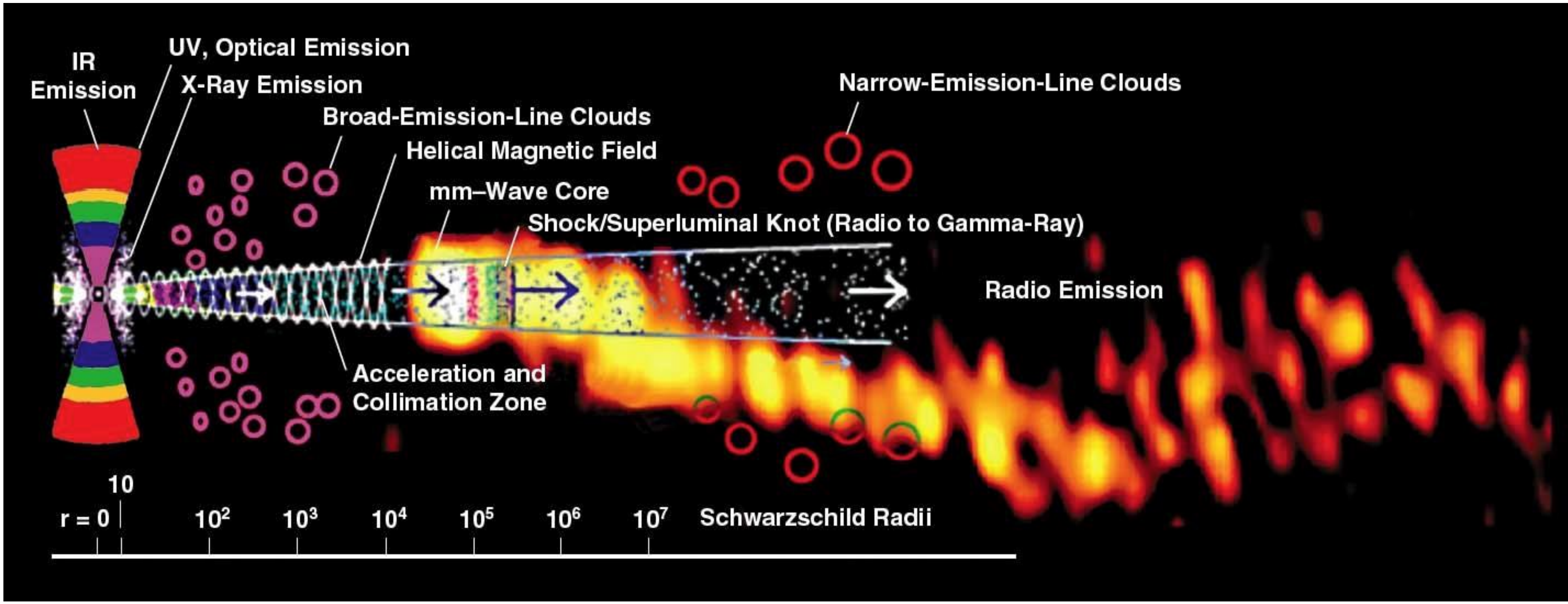
- **Source structure:** Move astrometry to K or Xka
- **Troposphere:** Built in WVRs
- **Clocks:** Phased plan to distribute clocks to southwestern stations then continental stations

- **Geometry/Resolution:**
  VLBA does very well in the northern hemisphere
  but at far end of reach $\delta \sim -30$ deg, loses accuracy.
  Astrometry would benefit from longer N-S baselines: southern outriggers?
  VLBA antennas in Mexico? at ALMA site?

- **Sensitivity:**
  Current systems use 0.5 GHz analog @ 2bit = 2 Gbps
  Large antennas are expensive, so gain sensitivity via
  increased bandwidth: 8 -32 Gbps?

Backup

Active Galactic Nuclei (*Marscher*)



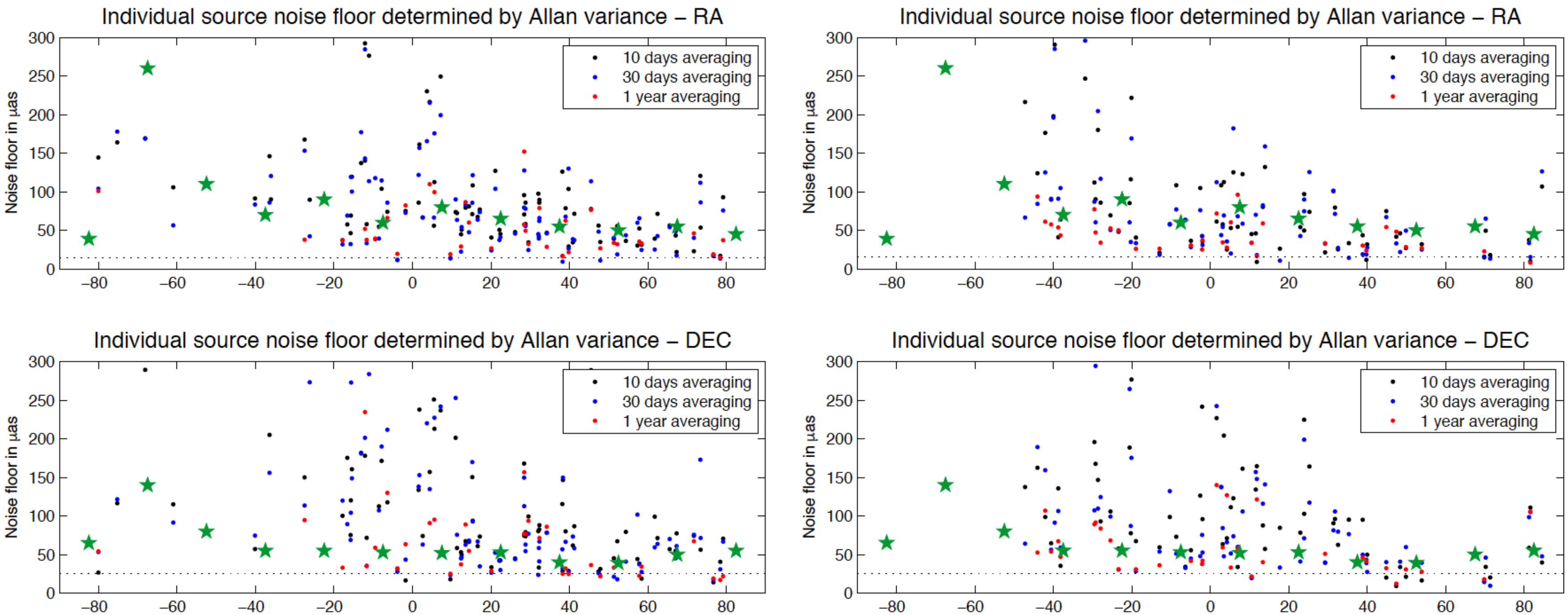
R~0.1-1 μas 1mas

Features of AGN: *Note the Logarithmic length scale.*
"Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core."

Credits: Alan Marscher, `Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science,VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)

SX VLBI systematic Floor ~ 20 to 30 μas?

Set of Flicker Noise sources | Set of White Noise sources



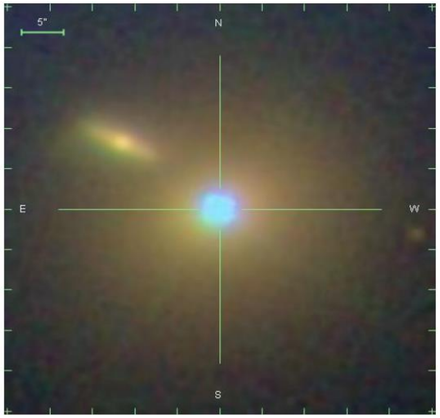
Green ★ : ICRF2 noise floor - average on sources in 15° declination bands.

Attention! This method uses ALL "good" sessions, contrary to the decimation test.

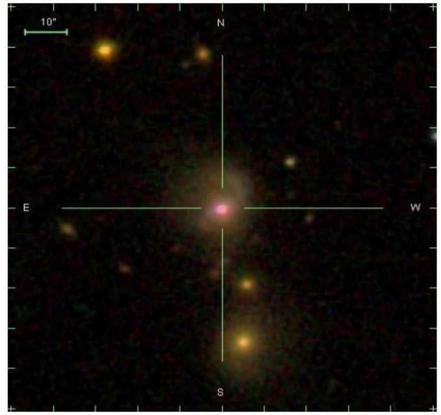
Le Bail+ (EVGA, 2017) use Allan variance test on position time histories
to determine when averaging no longer helps—systematic floor is encountered.
Structure part of this floor should be several times smaller at K (24 GHz) and Ka (32 GHz)

Optical vs. Radio systematics offsets

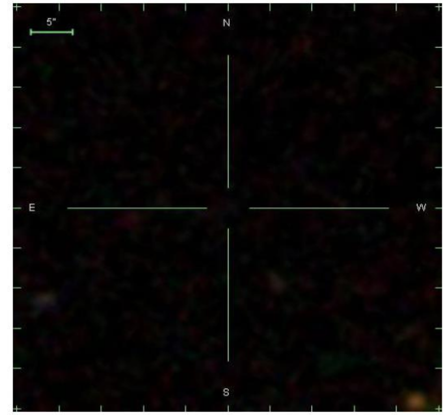
SDSS Optical images of quasars (scale 5-10 asec)



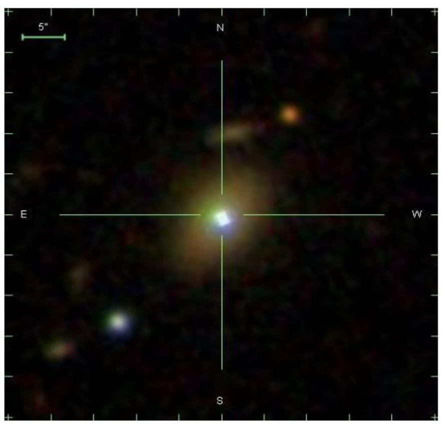
1101+384



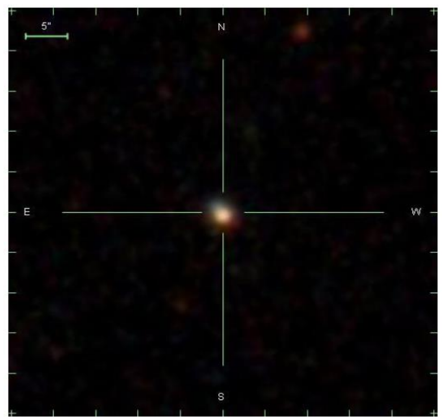
0007+106



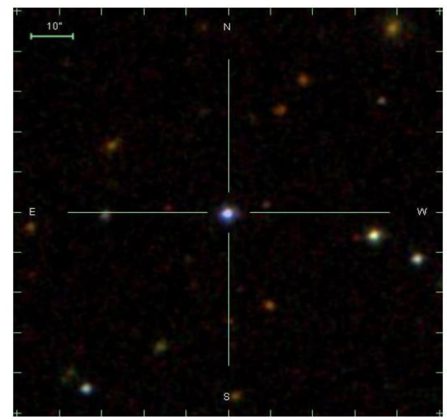
0920+390



1418+546



1514+192

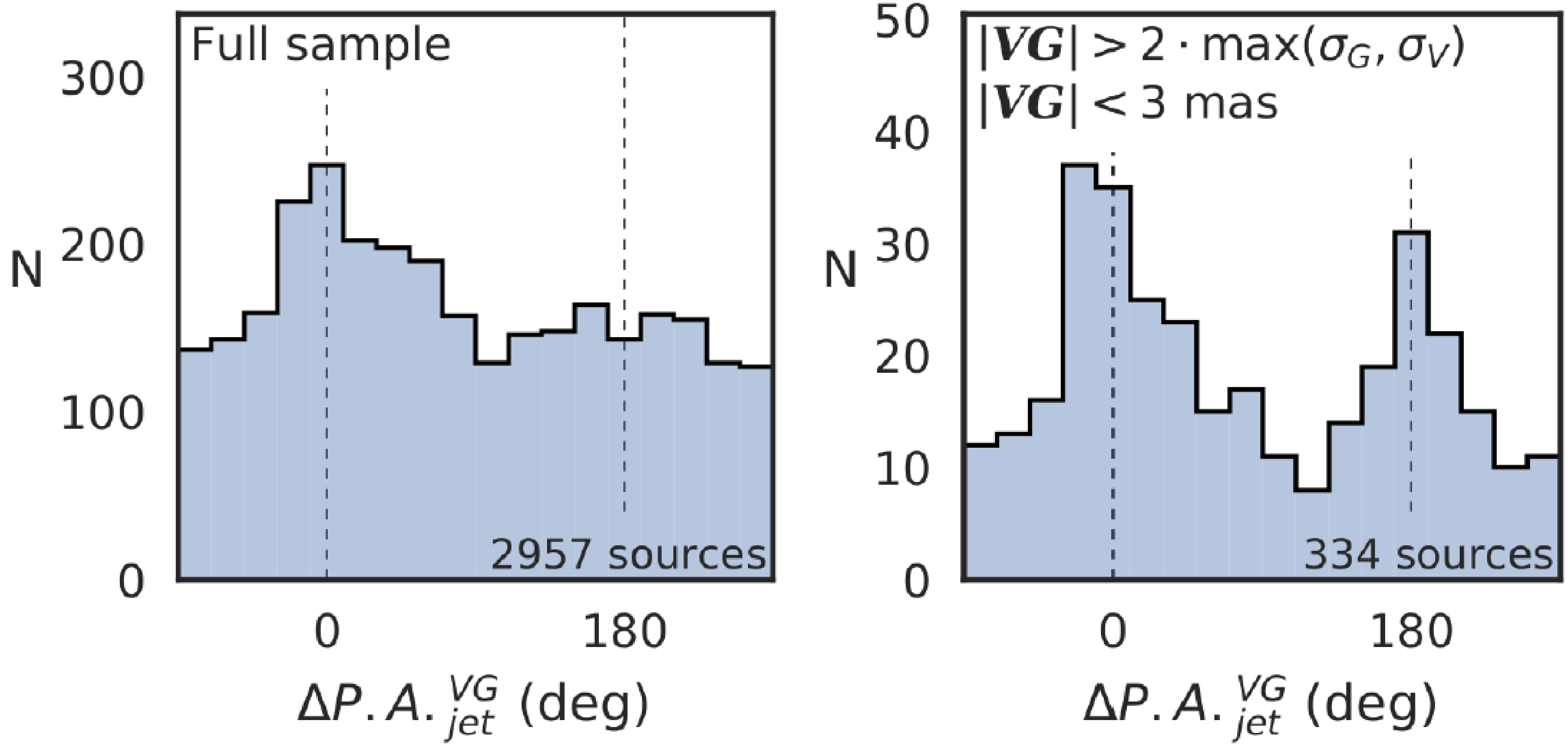


1546+027

Credit: SDSS

- Optical structure: The host galaxy may not be centered on the AGN or may be assymmetric.
- Optical systematics unknown, fraction of millarcsecond optical centroid offset?
- Optical imaging generally 10s of milliarcsecond. In general, no sub-mas optical imaging.

Optical vs. Radio systematics offsets



Petrov & Kovalev (MNRAS, 2017) show that optical-radio astrometric offsets Correlate with jet direction (or anti-direction).

They argue that the offsets are dominated by optical synchrotron jets.

Optical vs. Radio systematics offsets

Petrov & Kovalev (MNRAS, 2017)

- Example of optical jet in “nearby” 3C 264 would scale to ~milli-arsecond offsets at typical AGN distances.
- Optical synchrotron jets may be limiting factor in radio-optical astrometric agreement.
- VLBI interferometry “locks” onto the brightest component. Also extremely high resolution resolves out extended structures. So VLBI positions is close ot the core.
- Gaia optical image’s centroid averages all of the light distribution, jet included. “Beam” is 60 milliarcseconds.
- Optical may be more easily biased than radio.

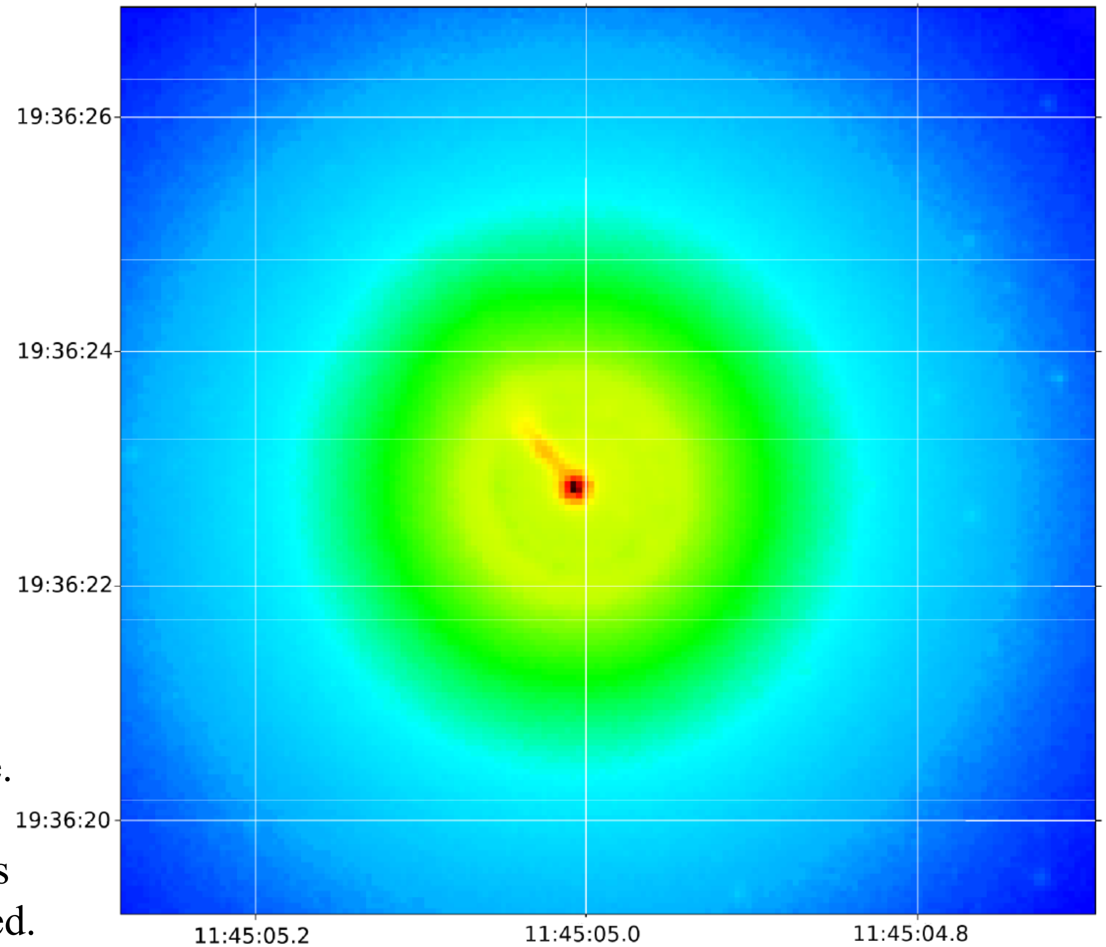


Figure 3. The archival HST image of 3C264 at 606 nm, HST project ID 13327 (Meyer et al. 2015).